Bibliometric Analysis of Academic Research in the Field of Utilizing Modern Information Technologies in Castles

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Abstract. The use of modern information technologies in heritage sites, such as castles, represents an innovative approach to their preservation, accessibility, and popularization. However, this topic has not yet been comprehensively explored from the perspective of academic research. The aim of this study is to examine academic interest in the use of modern technologies in castles through bibliometric and content analysis of relevant studies. The PICOC and PRISMA methods were used to identify, analyze, and synthesize the literature. The findings indicate that research in this area marginally addresses technologies such as big data, cloud computing, blockchain, and the Internet of Things. On the other hand, it partially focuses on the use of artificial intelligence, with the greatest interest from researchers directed towards virtual reality and augmented reality technologies. These technologies are most often employed to make historical landmarks accessible to the public through virtual tours, reconstructions of the original appearance of castles, or simulations of historical events, enabling vivid and engaging presentations of historical contexts. This study thus contributes to understanding current trends and gaps in research on the application of modern technologies to heritage sites and offers a basis for further research directions.

Keywords: Artificial intelligence, Castle, Cultural heritage, Information technology, Tourism, Virtual reality.

1. INTRODUCTION

Digitization represents one of the most significant trends in technological development, permeating all aspects of societal life (Vrana & Singh, 2021), including culture and tourism. In the context of preserving and presenting cultural heritage, digitization serves as a powerful tool that facilitates not only the modernization of heritage management approaches but also broadens accessibility to the public (Buragohain et al., 2024). This process profoundly impacts heritage sites such as castles and palaces, which play a crucial role in cultural identity and tourism appeal.

The application of digital technologies, such as virtual tours (Marin-Pantelescu et al., 2021), 3D scanning (Fino et al., 2022), augmented reality (Anand et al., 2023), and interactive applications (Saragih & Suyoto, 2020), provides new opportunities for the presentation and popularization of these landmarks. Simultaneously, these technologies offer tools for more efficient documentation and conservation (Rocha, 2021), contributing to long-term sustainability (El Archi et al., 2023; Ivars-Baidal et al., 2023) and making cultural heritage accessible to global audiences (Podara et al., 2021). Digitization opens avenues for innovative interactions with history, transforming not only how the public perceives these landmarks but also how they are managed.

This article focuses on bibliometric analysis as a tool to examine the scientific community's interest in the digitization of castles and palaces. The aim is to examine academic interest in the use of modern technologies in castles through bibliometric and content analysis of relevant studies. Bibliometric indicators provide insights into the technologies, methodologies, and research approaches most employed in this area.

The analysis aims to not only understand the current state of research on the digitization of cultural landmarks but also to identify gaps that could inspire future studies. Special attention is given to how the scientific community reflects on the implementation of digital technologies—such as artificial intelligence, virtual reality, or the Internet of Things—in the processes of conservation, documentation, and promotion of castles and palaces. The results of this bibliometric analysis can contribute to shaping future research strategies and emphasize the importance of digitization as a modern tool for preserving cultural heritage for future generations.

2. THEORETICAL FRAMEWORK

In the context of digitizing cultural heritage, it is essential to define the foundational concepts that establish the framework for applying intelligent technologies in tourism and the preservation of historical landmarks. A key concept in this regard is smart tourism, which refers to the application of modern information technologies (IT) to enhance service quality, visitor experiences, and the management of tourist destinations (Shin et al., 2023). This comprehensive approach integrates advanced technologies (Wang et al., 2020) to create interconnected, efficient, and sustainable tourism environments (Suanpang et al., 2022). Smart tourism is closely linked to the concept of "smart cities" and aims to transform traditional destinations into technologically advanced, inclusive, and sustainable environments (Habeeb & Weli, 2020).

Research on the digitization of cultural heritage, particularly historical landmarks like castles and palaces,

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spans multiple interdisciplinary fields. Each field addresses specific aspects of applying digital technologies for the preservation, management, and presentation of cultural landmarks. The modern technologies most utilized today include (Boršoš & Koman, 2023):

- Artificial Intelligence (AI): A field of computer science focused on developing algorithms and systems that perform tasks requiring human intelligence, such as learning, pattern recognition, decision-making, and prediction, often through machine learning and deep learning (Calvano et al., 2020; Das et al., 2015).
- Big Data: Technology and methodologies for processing and analyzing vast, heterogeneous datasets that cannot be effectively handled by traditional database tools, aimed at uncovering hidden patterns, trends, and associations (Awan et al., 2021; Koman et al., 2022).
- Blockchain: A distributed, decentralized technology based on encryption and consensus protocols that ensures transparency, immutability, and security for digital transactions and data without requiring a central intermediary (AlKubaisy & Al-Somali, 2023; Dritsas & Trigka, 2024).
- Virtual Reality (VR): A computer-generated simulated environment that allows users to interact with 3D objects and settings in real time using sensory devices like headsets and motion controllers (Jans et al., 2023; Suomalainen et al., 2020).
- Internet of Things (IoT): A network of interconnected physical devices equipped with sensors and software, enabling data collection, analysis, and sharing through the internet to optimize processes and automate decision-making (Atzori et al., 2010; Cirillo et al., 2020).
- Cloud Computing: A distributed computing infrastructure that provides flexible access to computational, storage, and application resources via the internet, allowing efficient hardware and software use on a pay-as-you-go basis (Alobaidi & Nuimi, 2022; Darbandi et al., 2022).

3. METHODOLOGY

This research is based on a bibliometric analysis aimed at examining academic interest in the use of modern technologies in castles. The methodological process of the study includes the following steps: 1) defining research questions, 2) parametric article search, 3) bibliometric analysis, 4) selection of relevant publications, 5) qualitative analysis, 6) evaluation of the current state of research.

3.1. Defining Research Questions

The research questions were developed using the PICOC framework, which structures the research according to defined parameters. This framework is particularly useful for systematically reviewing literature and defining relevant aspects of the study. The PICOC framework includes the following components:

- Population (P): The population targeted by the research consists of castles.
- Intervention (I): The intervention or technology being studied involves modern technologies and their applications in castle management.
- Comparison (C): The study compares the use of various technologies in castle management.
- Outcome (O): The outcomes measured or evaluated focus on the frequency and intensity of academic interest, as well as the main themes and discussions in the literature.
- Context (C): Contextual factors include castle types, geographic location, demographic characteristics of visitors, historical significance, and other relevant variables.

Based on the PICOC framework components, the research questions (RQ) were formulated as follows:

RQ1: What is the frequency and intensity of academic interest in the use of modern technologies in castles, as reflected in publications indexed in the Web of Science (WoS) and Scopus databases?

RQ2: What are the main themes and discussions dominating the academic literature regarding the application of modern technologies in castles?

RQ3: What is the functional value of modern technologies utilized in the context of castles?

3.2. Parametric Article Search

Before conducting the research, it was crucial to establish search parameters focused on addressing the defined research questions. This process involved careful selection of keywords and terminology used for the literature review, as well as the identification of relevant databases and other information sources. Defining the publication year parameter was also essential to ensure the relevance and currency of the obtained data. The article search parameters were as follows:

- Keywords: The selection of keywords was based on prior research (Boršoš & Koman, 2023), which defined modern technologies. The search string included the names of these technologies linked to castles, specifically: "*castle*" AND "*artificial intelligence*" OR "*cloud computing*" OR "*big data*" OR "*blockchain*" OR "*internet of things*" OR "*virtual reality*".
- Scientific Databases: The selected databases for this parameter were the most used ones, Web of Science (WoS) and Scopus.

- Publication Year: The time frame was determined based on a significant milestone marking the onset of the Fourth Industrial Revolution, during which modern technologies became pivotal factors influencing various domains, including cultural heritage and the management of historical sites. This approach ensured that the obtained data aligned with current trends and developments in technology.

3.3. Bibliometric Analysis

The bibliometric analysis focused on the quantitative assessment of existing literature. Two specific techniques were applied within this analysis: publication frequency analysis and keyword analysis. The software VOSviewer 1.6.20 was used to perform the bibliometric analysis.

- Publication Frequency Analysis: This analysis was conducted to monitor the number of published works over a specified period and identify trends in academic interest regarding modern technologies applied to castles.
- Keyword Analysis: The keyword analysis aimed to identify and classify the main concepts and themes dominating the literature on the use of modern technologies in castles.

3.4. Selection of Relevant Publications

The selection of relevant sources for this research is based on a thorough assessment of the available literature and the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). This method is used for the systematic processing and analysis of literary works and includes several key steps.

After searching for publications based on predefined search parameters, all relevant publications are gathered using Zotero 6.0.36 software. Then, the obtained sources are filtered according to: 1) title, 2) abstract, and 3) full text of the publication. This process is important to ensure the quality and relevance of the selected works. Publications that do not align with the research topic or are less relevant are excluded.

3.5. Qualitative Analysis

The qualitative analysis was carried out through content analysis. The object of the analysis was specifically modern technologies and their applications in the context of castles. For this purpose, the following research questions were formulated:

- What are the most significant thematic areas in the use of modern technologies at castles?
- What are the main arguments and discussions around the ethics, effectiveness, and impact of modern technologies on the operation and management of castles?
- What specific roles do modern technologies play in the management and operation of castles?
- What are the advantages and disadvantages of these modern technologies in practice?
- What are examples of successful implementations of modern technologies at castles?

3.6. Evaluation of the Current State of Research

Finally, it was necessary to evaluate the current state of research based on the conducted analyses. This step involved an overview of the latest trends and the identification of gaps in existing knowledge, highlighting areas that require further research. The contribution of the identified technologies in the field of cultural heritage digitization, particularly historical monuments such as castles and fortresses, was also assessed.

4. RESULTS

The results of the bibliometric analysis, which includes 468 publications obtained based on the defined search parameters (outlined in Chapter 3.2 – Parametric Article Search), show the development of interest in modern technologies in the field of cultural heritage digitization, specifically in castles and fortresses. The analysis highlights significant changes in technological trends that have occurred in recent years (Figure 1).

Figure 1: Network graph.

Around 2018, there was a noticeable increase in interest in technologies such as cloud computing, virtual reality (VR), and augmented reality (AR). These technologies were considered key at the time for creating interactive and accessible experiences for visitors to cultural monuments. Cloud computing enabled efficient management and distribution of digital content, while virtual and augmented reality started to be increasingly used to enhance the interactive presentation of historical monuments and create immersive experiences. Subsequently, around 2020, there was a rise in interest in big data, edge computing, and virtual reality. Big data and edge computing were seen as key for analyzing large volumes of data collected from IoT devices and optimizing heritage management, while virtual reality continued to play an important role in the digitization of cultural heritage. In 2021, researchers began to focus more on the Internet of Things (IoT), which became an essential tool for the collection and analysis of real-time data. IoT enables the interconnection of devices and systems, allowing for more efficient management and protection of cultural monuments. The year 2022 marked a turning point, with artificial intelligence (AI) emerging in the forefront, particularly in its advanced areas, such as deep learning, machine learning, and natural language processing (NLP). These technologies started to be applied to the analysis of historical data, predicting visitor behavior, and optimizing the management of cultural heritage through intelligent algorithms. AI and its various applications offer new opportunities to enhance the efficiency and personalization of tourist experiences.

This development shows the dynamics in the application of modern technologies to castles and fortresses, with each period introducing a new technological paradigm that responded to the changing needs and challenges in the management and protection of cultural heritage. The authors of the article then focused on a more detailed analysis of the individual technologies that emerged as key in the research. Each of these technologies was examined separately to better understand their specific applications, advantages, and potential in the context of cultural heritage digitization, especially in the field of castles and fortresses. These articles underwent a deeper analysis based on the PRISMA methodology, which allowed for the selection of relevant publications and ensured the objectivity and quality of the analysis. Indicators included the title of the publication (Prisma 1), the abstract (Prisma 2), and screening of the full text (Prisma 3), as outlined in Chapter 3.4 − Selection of Relevant Publications. When analyzing the relevance according to the PRISMA methodology in the six technological areas of cultural heritage digitization research focused on castles, it was found that four areas did not contain publications that addressed the issues defined in this article. These technologies are: big data, blockchain, cloud computing, and the Internet of Things.

Publications focused on the use of these four technologies do not explore their applicability in specific applications for the protection and management of castles as cultural heritage. Despite being modern technologies that are currently used not only in businesses but also in castles, these areas still do not attract the attention of researchers.

4.1. Big Data
Big data is used in cultural heritage digitization for trend analysis, planning tourist routes, optimizing

resources, improving monument management, and personalizing visitor experiences. Table 1 shows the development of big data research in the context of cultural heritage, where the number of publications began to grow from 2014, with the largest increase in 2020 and 2021 (12 and 14 publications, respectively). Between 2011 and 2016, the number of publications was very low (max. 2 per year), and in 2017, it increased to 9. Between 2019 and 2021, the number stabilized, and in 2022 and 2023, it slightly decreased but remained high.

Table 1: Development of Big Data Research in the Context of Cultural Heritage Digitization.

Year	Number of Publications	Duplicates	Prisma 1	Prisma 2	Prisma 3
2011	0	0	0	0	0
2012	0	0	0	0	0
2013	0	0	0	0	0
2014	1	0	0	0	0
2015	1	0	0	0	0
2016	2	0	0	0	0
2017	9	1	0	0	0
2018	6	0	0	0	0
2019	7	0	1	0	0
2020	12	0	0	0	0
2021	14	1	3	0	0
2022	8	0	1	0	0
2023	5	0	1	0	0
2024	7	1	0	0	0
Total	72	3	6	0	0

4.2. Blockchain

In the case of blockchain technology, the analysis showed that the frequency of publications on the application of this technology to castles and fortresses was relatively low. Of the total 22 publications that appeared between 2018 and 2024, most were concentrated in the years 2018 and 2022, with the number of publications in these years rising to 4 and 5, respectively. In 2023, 3 publications appeared, and in 2024, another 5 were published, with no duplicates or significant trends in the number of publications during this period.

Table 2: Development of Blockchain Research in the Context of Cultural Heritage Digitization.

Year	Number of Publications	Duplicates	Prisma 1	Prisma 2	Prisma 3
2011	0	0	0	0	0
2012	0	0	0	0	0
2013	0	0	0	0	0
2014	0	0	0	0	0
2015	0	0	0	0	0
2016	0	0	0	0	0
2017	0	0	0	0	0
2018	4	1	0	0	0
2019	2	0	0	0	0
2020	2	0	0	0	0
2021	1	0	0	0	0
2022	5	1	0	0	0
2023	3	0	1	0	0
2024	5	1	0	0	0
Total	22	3	1	0	0

4.3. Cloud Computing

The cloud computing technology has appeared in publications since 2011, with the number of publications gradually increasing over the years. Between 2013 and 2017, when publishing activity on this topic was recorded, there were 2 to 4 publications per year. From 2011 to 2024, a total of 31 papers were published, with the highest number of publications recorded in 2013 and 2017, with 3 and 4 papers, respectively. After 2017, the number of publications stabilized at a lower level, with 1 to 3 papers published annually.

Table 3: Development of Cloud Computing Research in the Context of Cultural Heritage Digitization

Year	Number of Publications	Duplicates	Prisma 1	Prisma 2	Prisma 3
2011	1	0	0	0	0
2012	1	0	0	0	0
2013	3	1	0	0	0
2014	2	1	0	0	0
2015	2	1	0	0	0
2016	0	0	0	0	0
2017	4	0	0	0	0
2018	4	0	0	0	0
2019	3	0	0	0	0
2020	2	0	0	0	0
2021	1	0	0	0	0
2022	2	0	0	0	0
2023	3	0	0	0	0
2024	3	0	0	0	0
Total	31	3	0	0	0

4.4. Internet of Things

Internet of Things (IoT) technology has been the subject of growing interest in academic literature from 2013 to 2024. In 2013 and 2014, 2 and 3 publications, respectively, focused on this technology. The following years saw a gradual increase in the number of publications, with the highest number recorded in 2019 and 2024, where 9 and 6 papers were published, respectively. Despite this growth, the number of publications on IoT in this field did not increase sharply every year, with slight decreases in 2015, 2020, and 2022.

Table 4: Development of Internet of Things Research in the Context of Cultural Heritage Digitization.

Year	Number of Publications	Duplicates	Prisma 1	Prisma 2	Prisma 3
2011	0	0	0	0	0
2012	0	0	0	0	0
2013	2	1	0	0	0
2014	3	1	0	0	0
2015	1	0	0	0	0
2016	2	0	0	0	0
2017	2	0	0	0	0
2018	3	1	1	0	0
2019	9	2	0	0	0
2020	2	0	0	0	0
2021	7	1	1	0	0
2022	4	0	0	0	0
2023	6	0	0	0	0
2024	6	0	0	0	0
Total	47	6	2	0	0

4.5. Artificial Intelligence

The development of research in the field of Artificial Intelligence (AI) in the context of cultural heritage digitization, particularly related to castles and palaces, shows a gradual increase in the number of publications over the years. The total number of publications in this field has been rising, with the most significant increase observed in 2023 and 2024, when the number of publications reached 32 and 40, respectively. This trend indicates a growing academic interest in AI applications for the management and protection of cultural heritage, which may be attributed to technological advancements and the expansion of research capacities in this area.

Between 2011 and 2014, research in AI was relatively limited, with a maximum of 7 publications in 2015. This increase can be attributed to the development of core AI technologies and the growing interest in their application in cultural heritage. After 2018, research in this area steadily intensified, with the largest jump in publications observed around 2020 to 2024. This trend highlights the increasing importance of AI in modernizing and optimizing processes for the protection, management, and presentation of historical monuments, as well as improving visitor experiences through personalized and predictive analytical tools.

Using the PRISMA methodology, the relevance of published works was analyzed, and out of a total of 165 publications, 9 duplicates were identified. After evaluating these publications according to the individual phases of PRISMA, 18 articles were included in the first phase (Prisma 1), 8 in the second phase (Prisma 2), and 3 in the third phase (Prisma 3). This approach ensures that only relevant publications, addressing the specific research topic, were included in the analysis.

Table 5: Development of Artificial Intelligence Research in the Context of Cultural Heritage Digitization.

Year	Number of Publications	Duplicates	Prisma 1	Prisma 2	Prisma 3
2011	3	0	0	0	0
2012	2	0	0	0	0
2013	4	0	0	0	0
2014	1	0	0	0	0
2015	7	3	1	1	0
2016	6	0	1	0	0
2017	5	0	1	0	0
2018	4	0	0	0	0
2019	11	2	1	1	0
2020	21	1	1	1	0
2021	16	1	0	0	0
2022	13	1	3	1	1
2023	32	0	3	2	1
2024	40	1	7	2	1
Total	165	9	18	8	3

The following articles were included among the relevant publications:

Table 6: Relevant publications.

Authors	Year	Title
Bile, A.; Tari, H.; Grinde, A.; Frasca, F.; Siani, A. M.; Fazio, E.	2022	Novel Model Based on Artificial Neural Networks to Predict Short-Term Temperature Evolution in Museum Environment
Bruno, S.; Galantucci, R. A.; Musicco, A.	2023	Decay detection in historic buildings through image-based deep learning
Hattori, S.; Fujidai, Y.; Sunayama, W.; Takahara, M.	2024	Effects of Machine Learning and Multi-Agent Simulation on Mining and Visualizing Tourism Tweets as Not Summarized but Instantiated Knowledge

Based on the analysis of these three publications, key thematic areas related to the use of Artificial Intelligence in castles and cultural heritage can be identified, along with discussions on the ethics, efficiency, and impact of this technology on the management and protection of monuments. All three articles focus on the application of modern technologies, particularly AI, machine learning (ML), and computer vision (CV), in the context of cultural heritage management and protection.

The first article focuses on the use of AI in smart tourism, where technologies such as machine learning and tweet analysis help manage and visualize tourist experiences at places like Hikone Castle (Hattori et al., 2024). The second article deals with computer vision and AI in assessing the condition of monuments, using advanced models to detect damage and monitor historic buildings such as castles (Bruno et al., 2023). The third article addresses predicting microclimatic conditions at castles and museums, where AI models help prevent climate-induced damage to art collections (Bile et al., 2022).

All three articles discuss ethical considerations and the effectiveness of using modern technologies in managing historical monuments, including castles. The first article addresses the challenge of capturing not only common but also unique signals from tourist data, which can lead to better personalized experiences for visitors, but also the difficulty of ensuring the accuracy of these analyses (Hattori et al., 2024). The second article emphasizes the ethical issues surrounding non-invasive technologies that replace traditional, time- and cost-intensive methods of heritage management (Bruno et al., 2023). The third article points to ethical concerns regarding the protection of cultural artifacts through predictions of microclimatic conditions, which can help prevent climate damage and preserve artworks (Bile et al., 2022).

Modern technologies play a key role in the management and operation of castles, whether in the analysis of tourist data, the assessment of monument condition, or the prediction of microclimatic conditions. These technologies enable more effective decision-making, better protection of cultural heritage, and personalized experiences for visitors. All analyzed publications highlight these points. The advantages of these technologies include increased efficiency, accuracy, and the ability to perform non-invasive analyses, leading to better monument preservation and enhanced visitor experiences. However, the challenges include the need for technical skills for implementing these technologies and the challenges related to the accuracy of models and the quality of data required for their proper functioning.

4.6. Virtual Reality

The development of research in the field of virtual reality (VR) within the context of cultural heritage digitization, specifically regarding castles and fortresses, shows a gradual increase in interest over the years. The analysis of the number of publications reveals that the initial interest in this technology was relatively low, with only two publications in 2011. However, from 2015 onwards, there was a significant leap in the number of publications, which has continued to increase to the present. This surge reflects the growing potential of virtual reality in the field of interactive experiences and its application to the protection and presentation of historical monuments.

2015 emerged as a pivotal point, marked by a substantial rise in publications, which can be attributed to technological innovations in virtual reality and a growing interest in its application in tourism. From this period onwards, the number of publications steadily increased, with dozens of publications appearing annually between 2018 and 2023. This trend suggests that the period saw more intense exploration of virtual reality applications in the domain of castles and fortresses, supported by technological advancements and a growing demand for the modernization of tourist and cultural experiences.

In recent years (2022-2024), the number of publications has stabilized at around 10-15 per year, indicating that research in this area has reached a certain level of stability. While there has not been a dramatic increase in research currently, there remains a strong interest in virtual reality applications, particularly in connection with digital reconstructions of historical monuments, interactive experiences, and their contribution to the modernization of cultural heritage.

The analysis based on the PRISMA methodology shows that, despite the growing number of publications, only a portion of them is considered relevant to the specific research question. After applying the PRISMA indicators, the number of publications was reduced, selecting only those that met the defined methodological criteria and were relevant to the given topic.

Table 7: Development of Virtual Reality Research in the Context of Cultural Heritage Digitization.

Year	Number of Publications	Duplicates	Prisma 1	Prisma 2	Prisma 3
2011	2	0	0	0	0
2012	1	0	1	1	1
2013	6	1	1	0	0
2014	3	1	1	1	1
2015	21	3	3	3	3
2016	5	0	0	0	0
2017	4	1	0	0	0
2018	10	3	2	1	1
2019	10	2	4	4	3
2020	15	2	2	2	1
2021	8	2	1	1	1
2022	13	3	4	4	3
2023	14	3	4	3	2
2024	6	2	0	0	0
Total	118	23	23	20	16

A total of 16 relevant publications were identified through the PRISMA methodology, focusing on the application of virtual reality (VR) in the context of digitizing castles and fortresses. This number shows that virtual reality is one of the most significant and extensively studied technologies in this field. Compared to other modern technologies also analyzed in the research, virtual reality occupies a dominant position. This is due to its wide range of applications, such as digital reconstructions of historical monuments, interactive experiences for visitors, and the modernization of cultural heritage presentation. This trend is supported by the increasing interest in VR among researchers and experts in digitization, indicating that this technology plays a key role in transforming cultural tourism and the protection of historical monuments. The relevant publications are listed in the following table:

Table 8: Relevant publications.

Authors	Year	Title
Salvatore, B.; De Feo, E.; D'Auria, S.; Guerriero, L.	2012	Survey and virtual restoration: The Castle of Magacela (Spain)
Komianos, V.; Kavvadia, E.; Oikonomou, K.	2014	Efficient and realistic cultural heritage representation in large scale virtual environments
Zupcánová, M.; Zupcán, L.	2015	Slanec Castle as Virtual Museum
Fukuda, T.; Ban, H.; Yagi, K; Nishiie, J.	2015	Development of High-Definition Virtual Reality for Historical Architectural and Urban Digital Reconstruction: A Case Study of Azuchi Castle and Old Castle Town in 1581
Barsanti, S. G.; Caruso, G.; Micoli, L.L.; Rodriguez, M.C.; Guidi, G.	2015	3D Visualization of Cultural Heritage Artefacts with Virtual Reality Devices
Leach, M.; Maddock, S.; Hadley, D.; Butterworth, C.; Moreland, J.; Dean, G.; Mackinder, R.; Pach, K.; Bax, N.; Mckone, M.; Fleetwood, D.	2018	Recreating Sheffield's medieval castle in situ using outdoor augmented reality
Melard, N.	2019	Lights on the dark ages – Multiscale 2D and 3D imagery for the study of medieval Graffiti at the château de Selles, Cambrai, France
Cesaria, F.; Cucinelli, A.M.; De Prezzo, G.; Spada, I.	2019	Gamification in Cultural Heritage: A Tangible User Interface Game for Learning About Local Heritage
Ruffino, P.A.; Permadi, D.; Gandino, E.; Haron, A.; Osello, A.; Wong, C.O.	2019	Digital technologies for inclusive cultural heritage: The case study of Serralunga d'Alba Castle
Papa, L.M.; D'Auria, S.	2020	Survey and digital modeling: A critical approach for the enhancement of the Castle of Ischia
Fiel, M.V.; Soler-Estrela, A.	2022	Interactive Virtual Reality applications for the enhanced knowledge of Spanish Mediterranean Fortress-Castles
De Fino, M.; Bruno, S.; Fatiguso, F.	2022	Dissemination, Assessment and Management of Historic Buildings by Thematic Virtual Tours and 3D Models
Ye, S.; Wu, T.; Jarvis, M.; Zhu, Y.	2022	Digital Reconstruction of Elmina Castle for Mobile Virtual Reality via Point-based Detail Transfer
De Paolis, L. T.; Chiarello, S.; Gatto, C.; Liaci, S.; De Luca, V.	2022	Virtual reality for the enhancement of cultural tangible and intangible heritage: The case study of the Castle of Corsano
de la Torre Fornés, I.; Maruenda, J. C.; González, D. M.	2023	Knowing the architectural heritage through graphic survey: the Castle of Ademuz
Kalinka, M.; Eriņš, I.; Vaivode, V.; Goldbergs, L.; Korna, I.; Smirnovs, R.; Gorovojs, K.	2023	3D Data Life in Cesis Medieval Castle in Latvia

One of the main aspects of digitization highlighted by the analyzed publications is the possibility of reconstructing historical objects into their original form using high-quality 3D models (Fukuda et al., 2015), which allows for their realistic display in a virtual reality environment (Barba et al., 2012; Fino et al., 2022). These reconstructions can serve not only for preservation and research purposes but also for creating interactive applications for the public, allowing visitors to virtually explore destroyed or inaccessible places, making them more accessible to a wider audience (De Paolis et al., 2022; Zupcanova & Zupcan, 2015).

Another frequently mentioned interactive technology is augmented reality (AR), which proves to be an excellent tool for enhancing the visitor experience when used to display reconstructed historical sites within their current context (Leach et al., 2018). These technologies also allow for adding extra informational layers, such as educational games or interactive information about artifacts (Cesaria et al., 2019), which significantly increases user engagement and interest in cultural heritage.

An interesting trend is the development of applications that combine various technologies (e.g., WebXR and GIS), enhancing the flexibility and accessibility of virtual tours that can function on a wide range of devices (Fiel & Soler-Estrela, 2021; Komianos et al., 2014). These tools not only help in the protection of monuments but also improve educational and research processes.

Despite these advantages, challenges related to digitization include the need for a balance between detail and application performance, particularly when processing large objects and complex datasets, which can affect the speed and efficiency of reconstruction (Komianos et al., 2014; Ye et al., 2022). Therefore, many projects focus on optimizing processes and utilizing effective tools such as HBIM (Historic Building Information Modeling) and photogrammetry, which allow for better processing and long-term use of 3D data for various purposes (Kalinka et al., 2023; Ruffino et al., 2019).

5. DISCUSSION

Digitalization is a broad phenomenon that is studied and implemented across many fields (Kuusisto, 2017; Parviainen et al., 2017), not just in cultural heritage. It is a process that allows the conversion of physical objects and information into digital formats, offering numerous advantages such as more efficient processing, storage, sharing, and analysis of data (Vartolomei & Avasilcai, 2019). These technologies have a profound impact on various sectors, with some of the most notable applications in education, healthcare, industry, and commerce.

Education is one of the areas where digitalization has undergone tremendous changes (Kalimullina et al., 2021). Online learning platforms, digital textbooks, interactive tools, and applications using augmented reality

(AR) and virtual reality (VR) have become common tools to enhance teaching and learning (Petrusevich, 2020). These technologies provide students and teachers access to rich digital content and new forms of interactive education that support the visualization of complex concepts and offer personalized learning experiences (Arısoy, 2022).

In healthcare, digitalization focuses on improving diagnosis, treatment, and patient management (Lapão, 2019). Electronic health records (EHR), telemedicine, diagnostic tools using artificial intelligence, and robotic surgical systems are just some of the technological innovations that enhance efficiency and accuracy in medicine (Gjellebæk et al., 2020; Menvielle et al., 2017). Digitalization also enables remote access to medical services, which is particularly useful in remote and underserved areas.

In industry, digitalization is often referred to as Industry 4.0 and involves the use of IoT (Internet of Things), artificial intelligence, automation, and digital manufacturing (Húdik et al., 2019; Koman & Bubeliny, 2020; Štaffenová & Kucharčíková, 2023). These technologies enable the optimization of manufacturing processes, improved efficiency, predictive maintenance of equipment, and product personalization. Digitalized production lines and robotics also reduce the need for manual labor, increase safety, and allow for faster adaptation of production to market needs (Ghobakhloo et al., 2021).

In commerce and services, digitalization focuses on transforming how companies interact with customers, manage inventories, sell products, and provide services (Escursell et al., 2021). Online shopping, digital payments, e-commerce platforms, and customer-focused services using artificial intelligence, such as chatbots, are examples that simplify customer interaction, increase convenience, and reduce costs (Chatterjee et al., 2022). Predicting trends and analyzing customer data are other areas where digitalization brings a competitive advantage.

Thus, digitalization expands its reach and introduces innovation into various fields, improving efficiency, accessibility, and the adaptation of technologies to the needs of modern societies and individuals. Often, it is useful to draw inspiration from the potential applications of modern technologies in fields that may not initially seem directly related. This interdisciplinary approach opens up new opportunities for process improvement, innovation, and the customization of technologies to meet specific needs. For example, methods and technologies used in manufacturing or healthcare, such as artificial intelligence, augmented reality, or IoT, can also find applications in the field of cultural heritage—such as in the management and digitization of historical sites like castles and palaces.

This is why research on the use of modern information technologies for castles is extremely important. The combination of inspiration from different industries and the application of advanced technologies can offer new ways to preserve, present, and make historical landmarks more accessible. Such an approach not only helps protect cultural heritage for future generations but also makes it more attractive to the general public, thereby supporting education, tourism, and interest in history.

6. CONCLUSION

The bibliometric analysis highlighted the dynamic technological development in the field of cultural heritage digitalization, focusing on castles and palaces. The results showed that technological trends have significantly changed over the years. While cloud computing, virtual reality, and augmented reality dominated around 2018, offering interactive experiences for visitors, later years saw the rise of big data, edge computing, and IoT, which enabled advanced data analysis and more efficient heritage management. Most recently, since 2022, artificial intelligence has emerged as a major breakthrough, being used for prediction, analysis, and the improvement of cultural heritage protection.

The analysis also revealed a lack of research on the application of technologies such as blockchain, big data, and cloud computing specifically in the management of castles. Despite their potential, these technologies have not been sufficiently explored in the context of cultural heritage preservation. Currently, researchers are focusing on the use of virtual reality in castle preservation and management. One of the most common applications is the creation of virtual tours that allow visitors to experience the authentic atmosphere of castles from the comfort of their homes. Another significant approach is the reconstruction of lost or damaged parts of castles using augmented reality, based on historical documents and archaeological research. This technology allows visitors to see what the castle looked like at the height of its glory. In addition, simulations of historical events, such as battles, royal ceremonies, and everyday life at castles, are becoming increasingly popular. Modern technologies can reconstruct these events so realistically that they provide viewers with a deeper experience and emotional connection to history. These applications not only bring the past to life but also expand educational opportunities and increase the attractiveness of cultural heritage to the public.

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